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AUTHOR: W. Podgorski, W. Davis
DESCRIPTION: Effects of an Offset Temperature on Constellation-X Segmented Optics with Epoxy Replication Layer

Summary

The current design for Constellation-X optical segments includes a thin epoxy layer over the substrate glass. The glass is “slumped” to shape on a forming mandrel at elevated temperature, then allowed to cool and harden. After the forming step an epoxy replication step may be performed. In this step a thin (10 μ m to 40 μ m) layer of epoxy is applied between the formed glass substrate and a “replication (or finishing)” mandrel. The epoxy is allowed to cure (at a slightly elevated temperature for some epoxy candidates) and then the finished optic segment is removed from the mandrel.

The replication epoxy and glass substrate have much different CTE’s, therefore the bi-layer composite of the two will exhibit a sensitivity to changes in temperature which is different from that of a single uniform CTE material. There are several questions arising from this issue:

1. The replication curing process may take place at an elevated temperature. What is the effect on “rest” optical figure of lowering the temperature from the curing temperature to assembly temperature? How does this effect vary with different epoxies?
2. What is the effect on optical performance of the epoxy/glass composite material as opposed to an all glass optic, given a change in bulk temperature of the optic?
3. How does the performance effect of the composite material compare with performance effects due to mis-match in housing/ glass CTE?

In summary, the housing to optic CTE mis-match (optic and housing attached in all 3 translational DOF) has the largest impact on performance. If this effect is mitigated by design, then the epoxy bi-layer effects with EP301 will show up as significant, in the few arcsec HPD per Degree C range. If OP30 is used then the bi-layer effect is negligible. In any case, the degree to which the housing and optic can be matched in overall CTE will be a major performance driver.

Optics Rest State

Figures 1, 2 and 3 illustrate the effects of the epoxy composite on “rest” state optical figure. Each of these cases was run with kinematic boundary conditions, setup so that the center azimuth of the optic (30 degrees) was undisturbed. In each case a negative one degree C temperature offset was applied as a load. The three plots show radial deformations for the following materials:

1. D236 glass only (440 μ thick) with 7.2ppm/degC CTE and 10.57×10^6 psi modulus
2. D236 glass (400 μ m) and Epotek OP30 epoxy (20 μ m). The OP30 CTE is 200ppm/deg C and modulus is 3000 psi
3. D236 glass (400 μ m) and Epotek EP301 epoxy (20 μ m). The EP301 CTE is 62ppm/deg C and modulus is 248,000 psi

These three cases are listed in order of increasing bi-layer temperature sensitivity (roughly proportional to product of CTE and modulus)

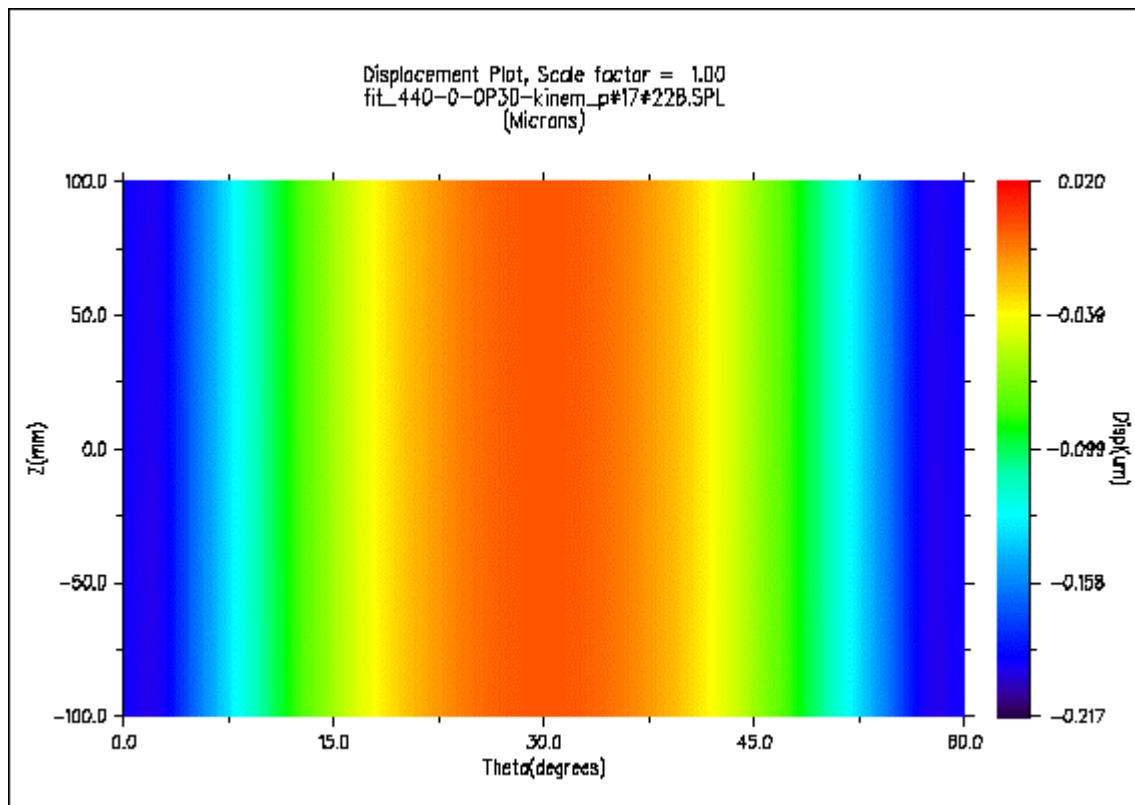


Figure 1 – Effect of -1 Deg C ΔT on All Glass Optic (Kinematic BC)

In all three cases the primary deformation is a bending inwards (towards smaller radii) of the ends of the optic. To get a more quantitative estimate of the optical deformations, each of the three deformation cases was fit with Legendre-Fourier polynomials, using 3 Legendre terms and 12 Fourier. The full fit outputs are included in Appendix A. It turned out that the most significant terms were 0θ , $\cos(6\theta)$ and $\cos(12\theta)$.

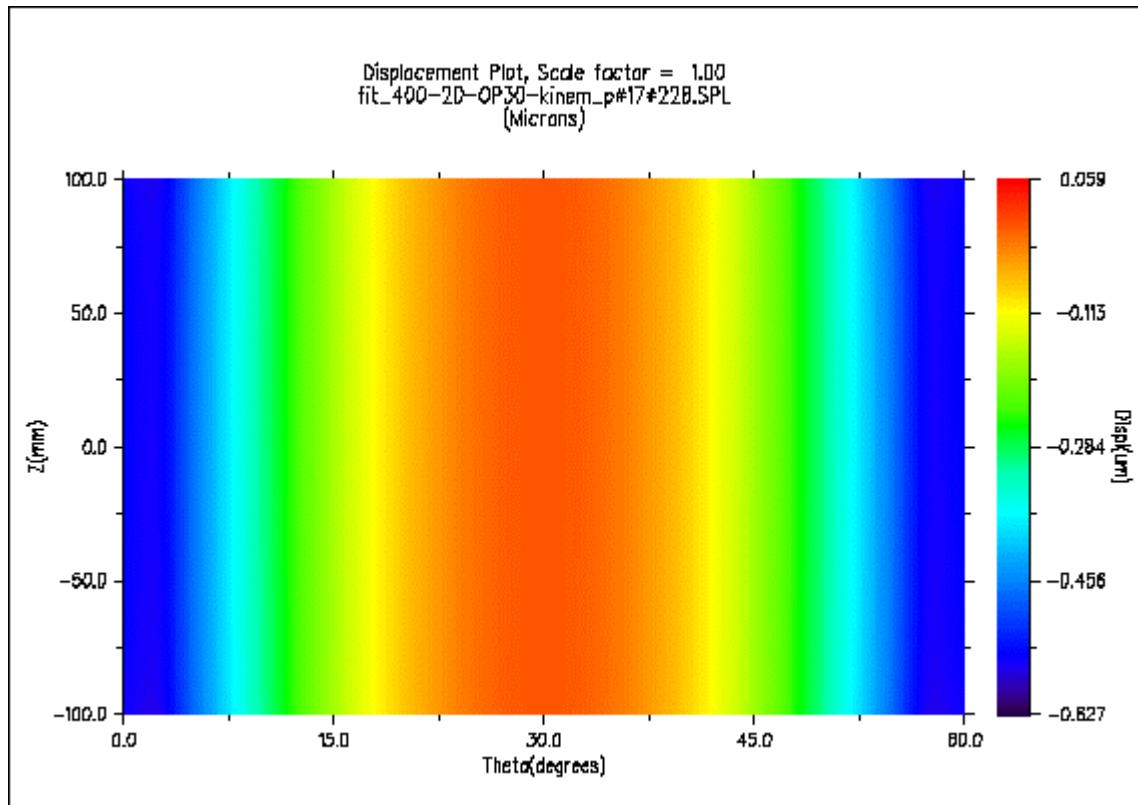


Figure 2 – Effect of -1 Deg C ΔT on OP30 Epoxy/Glass Optic (Kinematic BC)

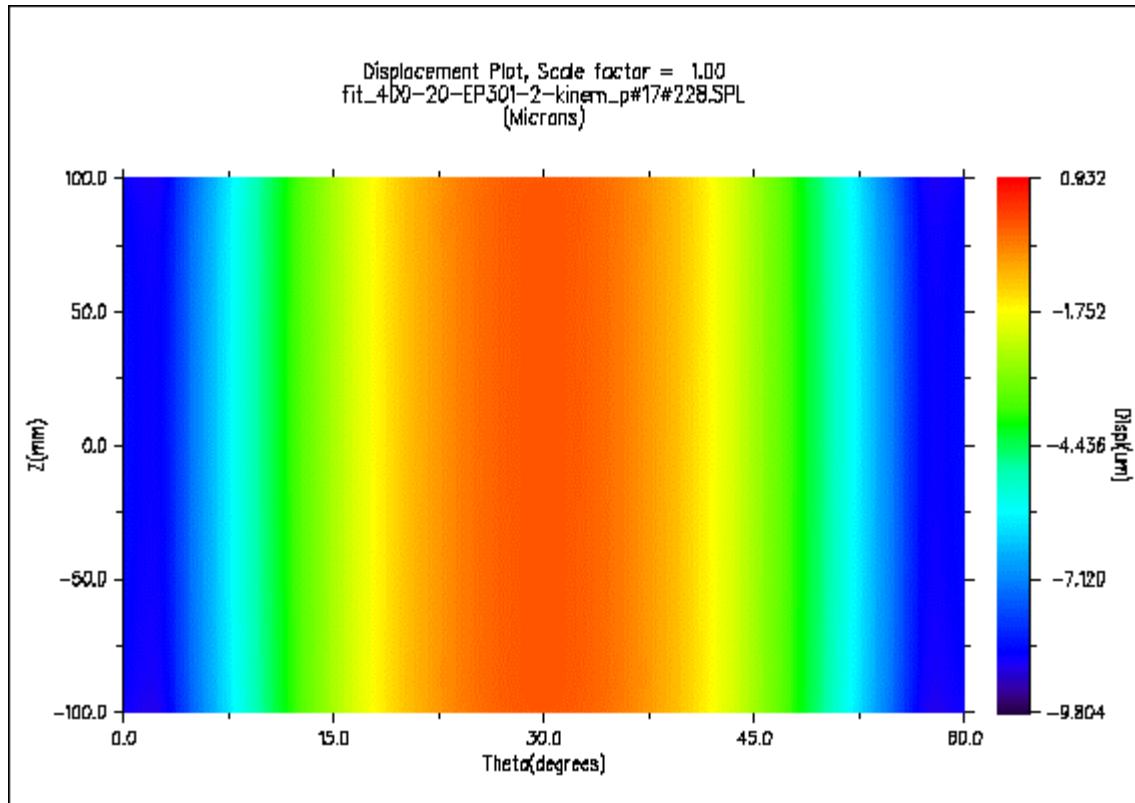


Figure 3 – Effect of -1 Deg C ΔT on EP301 Epoxy/Glass Optic (Kinematic BC)

The larger of the Legendre-Fourier coefficients from the data fits are shown in Table 1. The pure sag coefficients (L2) are under 0.05 μm even for the largest deformations (EP301).

POLYNOMIAL COEFFICIENT SUMMARY

TYPE OF POLYNOMIALS: LEG/FOUR
 # OF POLY'S (LEG, FOUR, TOT): 3 12 75
 # OF GOOD DATA POINTS: 7560
 SIGMA**2 OF ACTUAL DATA: 1.0591E-08

L	INDECES MCOS MSIN	COEFFICIENT VALUE	SIGMA**2 OF POLY #I	SIGMA**2 OF POLY'S 1 TO I	SIGMA**2 OF DATA - POLY'S
<hr/>					
Glass Only					
0		-7.7854E-05	6.0613E-09	6.0613E-09	-2.3047E-06
1		2.3141E-07	1.7851E-14	6.0613E-09	4.5298E-09
2		1.6312E-09	5.3214E-19	6.0613E-09	4.5298E-09
0 6		-9.2765E-05	4.3027E-09	1.0364E-08	2.2718E-10
1 6		2.7630E-07	1.2724E-14	1.0364E-08	2.2717E-10
2 6		3.1179E-09	9.7211E-19	1.0364E-08	2.2717E-10
0 12		-1.9885E-05	1.9771E-10	1.0562E-08	2.9459E-11
1 12		6.0429E-08	6.0861E-16	1.0562E-08	2.9459E-11
2 12		2.1685E-09	4.7026E-19	1.0562E-08	2.9459E-11
OP30					
0		-2.2094E-04	4.8814E-08	4.8814E-08	-2.2722E-06
1		7.6245E-07	1.9378E-13	4.8814E-08	3.6962E-08
2		-1.7810E-06	6.3438E-13	4.8815E-08	3.6962E-08
0 6		-2.6485E-04	3.5072E-08	8.3887E-08	1.8560E-09
1 6		9.3212E-07	1.4481E-13	8.3887E-08	1.8559E-09
2 6		-2.5202E-06	6.3512E-13	8.3888E-08	1.8551E-09
0 12		-5.6761E-05	1.6109E-09	8.5499E-08	2.4009E-10
1 12		2.2400E-07	8.3627E-15	8.5499E-08	2.4008E-10
2 12		-1.4395E-06	2.0721E-13	8.5499E-08	2.3983E-10
EP301					
0		-3.4226E-03	1.1714E-05	1.1714E-05	6.6205E-06
1		1.2720E-05	5.3931E-11	1.1714E-05	8.9296E-06
2		-4.1795E-05	3.4936E-10	1.1714E-05	8.9292E-06
0 6		-4.1154E-03	8.4681E-06	2.0183E-05	4.4893E-07
1 6		1.5639E-05	4.0765E-11	2.0183E-05	4.4889E-07
2 6		-5.9103E-05	3.4932E-10	2.0183E-05	4.4846E-07
0 12		-8.8192E-04	3.8889E-07	2.0572E-05	5.8090E-08
1 12		3.7921E-06	2.3967E-12	2.0572E-05	5.8088E-08
2 12		-3.3578E-05	1.1275E-10	2.0572E-05	5.7951E-08

Table 1 – Legendre Fourier Coefficients for Three Cases

Optical Performance Cases

Our intent in looking at optical performance was NOT to get a final, definitive prediction of thermally induced performance impacts, but only to show trends and sensitivities which may be used to guide the design process. We therefore ran some cases which are physically unrealistic, but interesting in that they help to highlight differences.

The effects on optical performance of the bi-layer temperature sensitivity were computed by raytrace analysis. A large number of different cases were run, using different epoxies, boundary conditions and epoxy thickness. Cases were also run for deformations on both P and H and on P only. The list below summarizes the parameters which were varied.

1. Epoxies:
 - a. OP30
 - b. EP301
 - c. NO epoxy
2. Constraints:
 - a. Kinematic constraints
 - b. Radial constraints (tangential/axial/rotations free)
 - c. Full translational constraints consistent with a rigid, zero CTE housing
 - d. Imposed translational displacements consistent with a rigid aluminum housing
3. Epoxy thickness:
 - a. 10 μm
 - b. 20 μm
 - c. 40 μm
 - d. None
4. Imposed Deformations:
 - a. P and H deformations
 - b. P deformations only (H has no deformations).
5. Aperture size (40 degrees to 60 degrees)

The epoxy and glass properties used are given in Table 2.

Material	CTE (ppm/Degree C)	E (psi)	CTE * E
D236 Glass	7.2 (5.4 in April analyses)	10.57×10^6	72 Million
EP301 Epoxy (Epotek)	62	248,000	15.3 Million
OP30 Epoxy (Epotek)	200	3,000	0.2 Million

Table 2 – Material Properties

Results of the analyses are shown plotted in Figure 4. In this plot all runs were made with a wedge shaped aperture 52 degrees in extent. This aperture is close to that of the current housing design. The results are mildly sensitive to aperture size because the deformations in most cases become worse near the edges.

Results are plotted as a function of epoxy thickness, but on a **LOG** scale. Fourteen different cases are shown, summarized in Table 3.

Case	Epoxy Type	Deformations	Epoxy Thickness (μm)	Constraints	Notes
1	EP301	P & H	0, 10, 20, 40	Radial	2.8 arcsec HPD max
2	EP301	P & H	0, 10, 20, 40	Kinematic	2.2 arcsec HPD max
3	EP301	P, H Zero	0, 10, 20, 40	Radial	1.4 arcsec HPD max
4	EP301	P, H Zero	0, 10, 20, 40	Kinematic	1.1 arcsec HPD max
5	OP30	P & H	0, 10, 20, 40	Radial	0.14 arcsec HPD max
6	OP30	P & H	0, 10, 20, 40	Kinematic	0.11 arcsec HPD max
7	OP30	P, H Zero	0, 10, 20, 40	Radial	0.07 arcsec HPD max
8	OP30	P, H Zero	0, 10, 20, 40	Kinematic	0.05 arcsec HPD max
9	EP301	P & H	10, 40	Radial	April
10	EP301	P & H	10, 40	Kinematic	April
11	OP30	P & H	20	Zero displacements all 3 DOF (rigid housing)	18 arcsec HPD
12	OP30	P & H	20	Imposed displacements all 3 DOF (AL Housing)	40 arcsec HPD
13	None	P & H	0	Zero displacements all 3 DOF (rigid housing)	17 arcsec HPD
14	None	P & H	0	Imposed displacements all 3 DOF (AL Housing)	37 arcsec HPD

Table 3 – Case Summaries, all for -1 Degree C ΔT and 52 Degree Wedge Aperture

Epoxy/Glass Bilayer Effects for 52 Degree Aperture and -1 Degree C Delta T

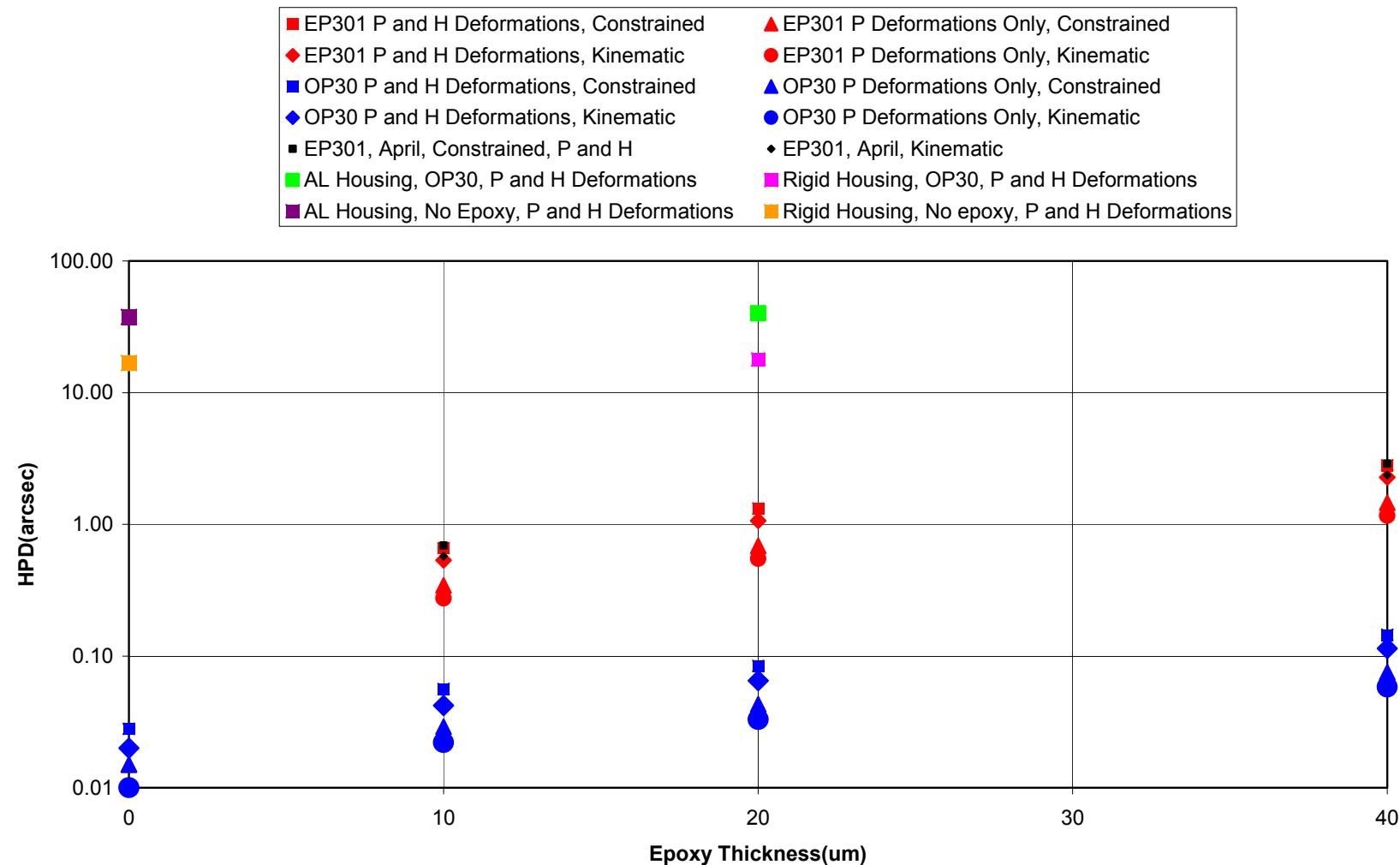


Figure 4 – Optical Performance of Various Cases

Discussion

Note first that the Half Power Diameter (HPD) results in Figure 4 had to be plotted on a log scale because of the large differences in overall sensitivities to temperature. The highest (by far) sensitivities were for the cases in which displacement boundary conditions in all 3 translational DOF (radial, axial, tangential) simulating an Aluminum housing were applied. The presence of the epoxy made little difference in the results for these cases. From the studies done earlier, we know that the performance is most sensitive to axial displacement mis-match between the optic and housing. In this case the housing shrinks more than the optic, imposing compressive loads onto the optic at the attachment points, top and bottom. This causes a dimpling effect which can be seen in Figure 5.

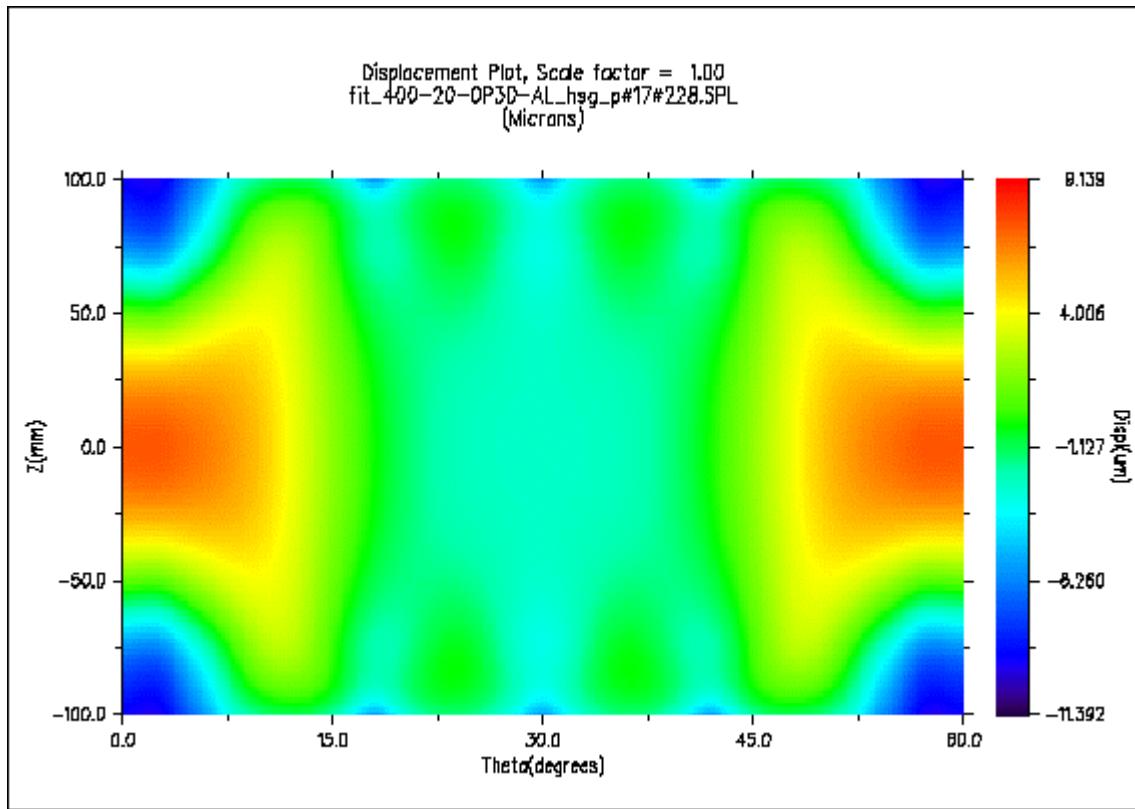


Figure 5 – Displacement Plot, AL Housing Case

The next highest sensitivity was for the simulated rigid housing in which the optic is shrinking but the housing is not. This causes similar dimpling in the optic but in the opposite radial direction, as shown in Figure 6.

To see the impacts of the epoxy bi-layer on performance, the performance dominating axial constraint must be relaxed. The four EP301 cases shown in Figure 4 have sensitivities ranging from about 1 arcsec/Degree C to 3 arcsec/Degree C, depending on

epoxy thickness, constraints and imposed deformations. The radially constrained case with P & H deformations applied is highest. This case might be obtained if the axial CTE's of the bi-layer optic were perfectly matched to the housing.

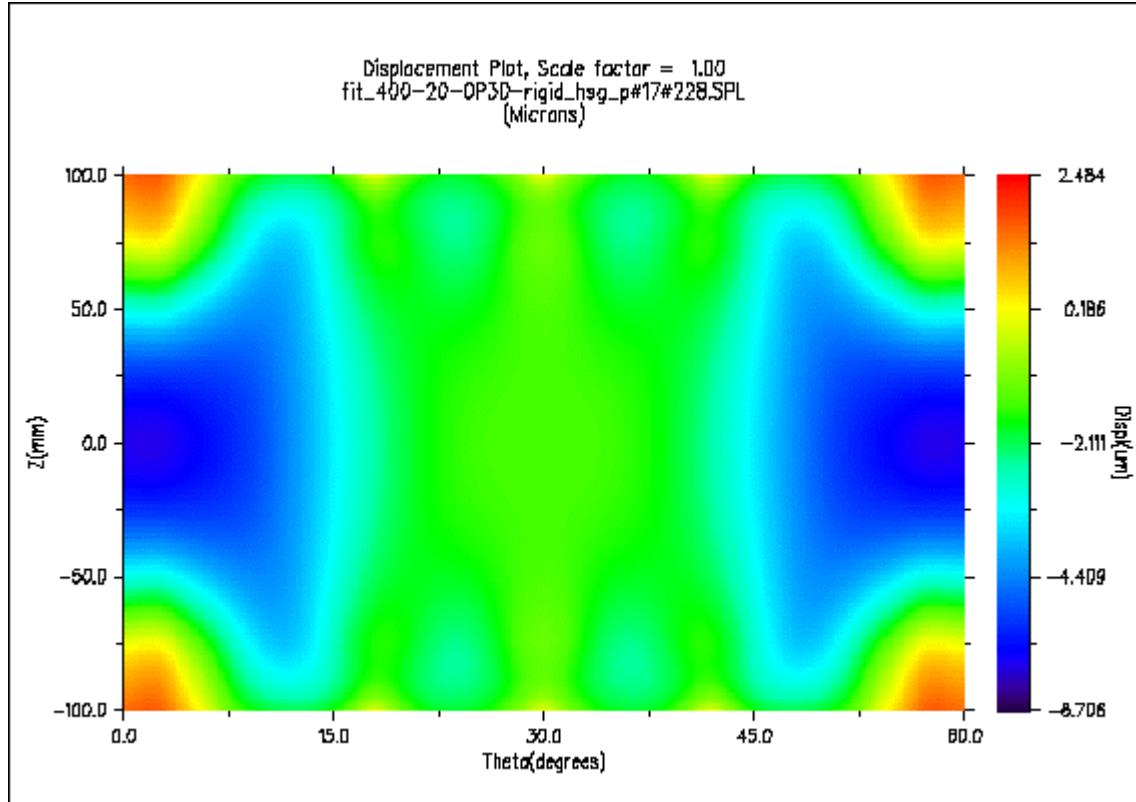


Figure 6 – Displacement Plot, “Rigid” Housing Case

Figure 7 shows the displacements from the EP301 case with radial constraints and 20 μm epoxy thickness. The displacements in this case differ from that with kinematic constraints. The effect of the radial constraint is to cause the bulging seen at the edges of the optic.

Another interesting feature of this set of cases is that the displacements are driven by the presence of the epoxy on the glass. Figure 8 shows that the displacements for a glass only case with radial constraints are very small.

The OP30 cases shown in Figure 4 have performance impacts in the 0.1 arcsec/Degree C range, an order of magnitude below the EP301 cases. This is consistent with the fact that the combined CTE times modulus for OP30 is almost two orders of magnitude below that of EP301.

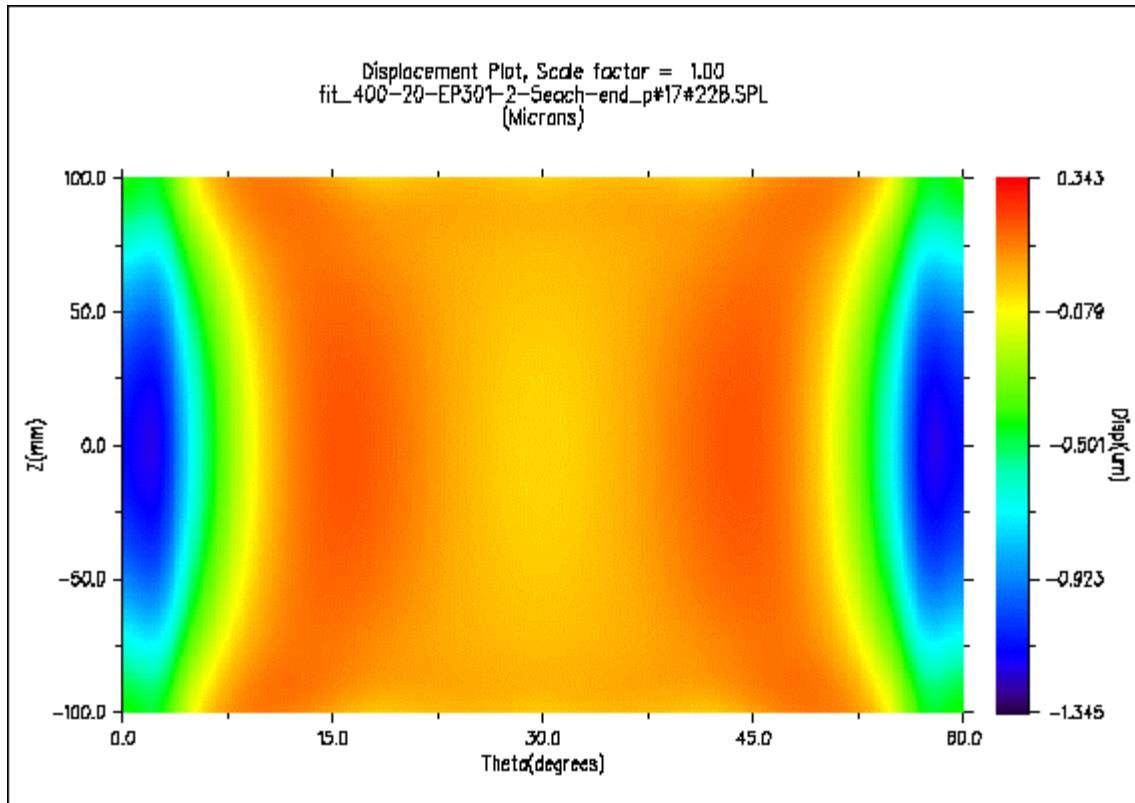


Figure 7 – Displacement Plot, EP301 Case, Radial Constraint, 20 μm Epoxy Thickness

In summary, the housing to optic CTE mis-match (optic and housing attached in all 3 translational DOF) has the largest impact on performance. If this effect is mitigated by design, then the epoxy bi-layer effects with EP301 will show up as significant, in the few arcsec HPD per Degree C range. If OP30 is used then the bi-layer effect is negligible. In any case, the degree to which the housing and optic can be matched in overall CTE will be a major performance driver.

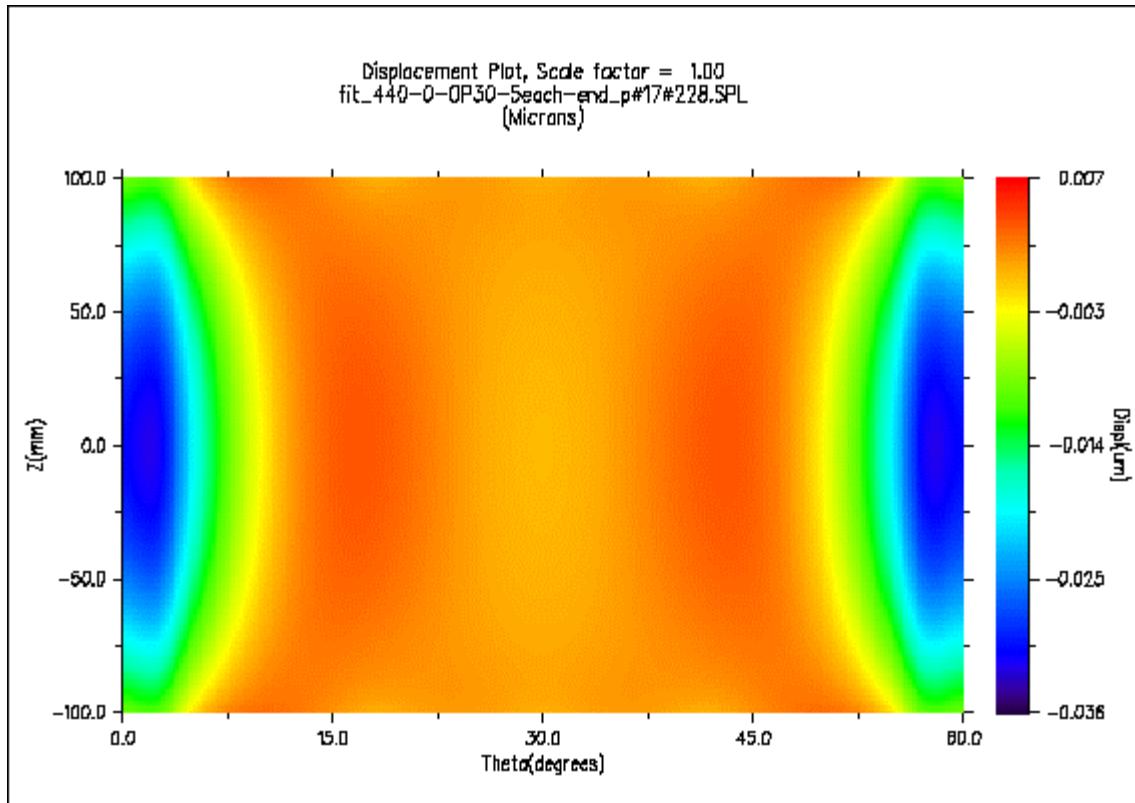


Figure 8 – Glass Only, No Epoxy, Radial Constraint Only

Glass Only

Appendix

POLYNOMIAL COEFFICIENT SUMMARY

TYPE OF POLYNOMIALS:			LEG/FOUR	
# OF POLY'S (LEG, FOUR, TOT):			3	12
# OF GOOD DATA POINTS:			7560	
SIGMA**2 OF ACTUAL DATA:			1.0591E-08	
INDECES L MCOS MSIN	COEFFICIENT VALUE	SIGMA**2 OF POLY #I	SIGMA**2 OF POLY'S 1 TO I	SIGMA**2 OF DATA - POLY'S
0	-7.7854E-05	6.0613E-09	6.0613E-09	-2.3047E-06
1	2.3141E-07	1.7851E-14	6.0613E-09	4.5298E-09
2	1.6312E-09	5.3214E-19	6.0613E-09	4.5298E-09
0 1	8.7398E-12	3.8192E-23	6.0613E-09	4.5298E-09
1 1	8.5435E-13	1.2165E-25	6.0613E-09	4.5298E-09
2 1	-9.3455E-13	8.7339E-26	6.0613E-09	4.5298E-09
0 2	5.6728E-13	1.6090E-25	6.0613E-09	4.5298E-09
1 2	5.7926E-13	5.5925E-26	6.0613E-09	4.5298E-09
2 2	5.1900E-13	2.6936E-26	6.0613E-09	4.5298E-09
0 3	-3.7217E-10	6.9254E-20	6.0613E-09	4.5298E-09
1 3	-1.4430E-09	3.4703E-19	6.0613E-09	4.5298E-09
2 3	-2.5779E-09	6.6456E-19	6.0613E-09	4.5298E-09
0 4	3.4697E-12	6.0193E-24	6.0613E-09	4.5298E-09
1 4	6.1853E-13	6.3763E-26	6.0613E-09	4.5298E-09
2 4	2.1068E-13	4.4385E-27	6.0613E-09	4.5298E-09
0 5	5.4543E-12	1.4875E-23	6.0613E-09	4.5298E-09
1 5	7.3646E-13	9.0396E-26	6.0613E-09	4.5298E-09
2 5	-4.8549E-13	2.3570E-26	6.0613E-09	4.5298E-09
0 6	-9.2765E-05	4.3027E-09	1.0364E-08	2.2718E-10
1 6	2.7630E-07	1.2724E-14	1.0364E-08	2.2717E-10
2 6	3.1179E-09	9.7211E-19	1.0364E-08	2.2717E-10
0 7	6.9004E-12	2.3808E-23	1.0364E-08	2.2717E-10
1 7	5.6355E-13	5.2931E-26	1.0364E-08	2.2717E-10
2 7	-1.1577E-12	1.3403E-25	1.0364E-08	2.2717E-10
0 8	1.2170E-12	7.4056E-25	1.0364E-08	2.2717E-10
1 8	2.5268E-13	1.0641E-26	1.0364E-08	2.2717E-10
2 8	7.0957E-13	5.0348E-26	1.0364E-08	2.2717E-10
0 9	-3.6141E-10	6.5307E-20	1.0364E-08	2.2717E-10
1 9	-1.5771E-09	4.1456E-19	1.0364E-08	2.2717E-10
2 9	-2.4721E-09	6.1114E-19	1.0364E-08	2.2717E-10
0 10	6.5619E-12	2.1530E-23	1.0364E-08	2.2717E-10
1 10	4.5538E-13	3.4562E-26	1.0364E-08	2.2717E-10
2 10	1.1182E-13	1.2504E-27	1.0364E-08	2.2717E-10
0 11	1.8291E-12	1.6728E-24	1.0364E-08	2.2717E-10
1 11	4.3859E-13	3.2061E-26	1.0364E-08	2.2717E-10
2 11	-1.8545E-13	3.4393E-27	1.0364E-08	2.2717E-10
0 12	-1.9885E-05	1.9771E-10	1.0562E-08	2.9459E-11
1 12	6.0429E-08	6.0861E-16	1.0562E-08	2.9459E-11
2 12	2.1685E-09	4.7026E-19	1.0562E-08	2.9459E-11
0 1	-3.0564E-13	4.6707E-26	1.0562E-08	2.9459E-11
1 1	4.0367E-13	2.7159E-26	1.0562E-08	2.9459E-11

2	1	-3.3420E-14	1.1169E-28	1.0562E-08	2.9459E-11
0	2	-3.7066E-13	6.8696E-26	1.0562E-08	2.9459E-11
1	2	3.0730E-13	1.5738E-26	1.0562E-08	2.9459E-11
2	2	-5.4253E-13	2.9434E-26	1.0562E-08	2.9459E-11
0	3	-1.9377E-12	1.8774E-24	1.0562E-08	2.9459E-11
1	3	3.1039E-14	1.6057E-28	1.0562E-08	2.9459E-11
2	3	3.6335E-14	1.3202E-28	1.0562E-08	2.9459E-11
0	4	-1.3239E-12	8.7641E-25	1.0562E-08	2.9459E-11
1	4	-3.8190E-13	2.4308E-26	1.0562E-08	2.9459E-11
2	4	1.1972E-13	1.4334E-27	1.0562E-08	2.9459E-11
0	5	-1.1370E-12	6.4643E-25	1.0562E-08	2.9459E-11
1	5	1.9866E-13	6.5775E-27	1.0562E-08	2.9459E-11
2	5	4.1448E-13	1.7179E-26	1.0562E-08	2.9459E-11
0	6	4.4051E-12	9.7025E-24	1.0562E-08	2.9459E-11
1	6	-2.4696E-14	1.0165E-28	1.0562E-08	2.9459E-11
2	6	2.7736E-13	7.6931E-27	1.0562E-08	2.9459E-11
0	7	-4.4226E-12	9.7795E-24	1.0562E-08	2.9459E-11
1	7	6.2071E-13	6.4213E-26	1.0562E-08	2.9459E-11
2	7	6.3199E-13	3.9941E-26	1.0562E-08	2.9459E-11
0	8	5.8846E-13	1.7314E-25	1.0562E-08	2.9459E-11
1	8	2.2086E-13	8.1297E-27	1.0562E-08	2.9459E-11
2	8	-9.4452E-13	8.9212E-26	1.0562E-08	2.9459E-11
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1	9	8.9495E-14	1.3349E-27	1.0562E-08	2.9459E-11
2	9	7.9948E-14	6.3916E-28	1.0562E-08	2.9459E-11
0	10	-4.0854E-12	8.3452E-24	1.0562E-08	2.9459E-11
1	10	-4.8437E-13	3.9102E-26	1.0562E-08	2.9459E-11
2	10	3.6404E-13	1.3252E-26	1.0562E-08	2.9459E-11
0	11	4.2558E-12	9.0557E-24	1.0562E-08	2.9459E-11
1	11	6.2643E-13	6.5402E-26	1.0562E-08	2.9459E-11
2	11	6.3621E-13	4.0476E-26	1.0562E-08	2.9459E-11
0	12	1.0296E-11	5.3008E-23	1.0562E-08	2.9459E-11
1	12	3.6090E-14	2.1708E-28	1.0562E-08	2.9459E-11
2	12	2.5523E-13	6.5140E-27	1.0562E-08	2.9459E-11

OP30

POLYNOMIAL COEFFICIENT SUMMARY

TYPE OF POLYNOMIALS: LEG/FOUR
 # OF POLY'S (LEG, FOUR, TOT): 3 12 75
 # OF GOOD DATA POINTS: 7560
 SIGMA**2 OF ACTUAL DATA: 8.5816E-08

L	INDECES MCOS MSIN	COEFFICIENT VALUE	SIGMA**2 OF POLY #I	SIGMA**2 OF POLY'S 1 TO I	SIGMA**2 OF DATA - POLY'S
0		-2.2094E-04	4.8814E-08	4.8814E-08	-2.2722E-06
1		7.6245E-07	1.9378E-13	4.8814E-08	3.6962E-08
2		-1.7810E-06	6.3438E-13	4.8815E-08	3.6962E-08
0	1	2.4059E-11	2.8941E-22	4.8815E-08	3.6962E-08
1	1	-4.3133E-13	3.1008E-26	4.8815E-08	3.6962E-08
2	1	-3.8289E-13	1.4661E-26	4.8815E-08	3.6962E-08
0	2	2.3772E-12	2.8256E-24	4.8815E-08	3.6962E-08
1	2	-6.1869E-14	6.3795E-28	4.8815E-08	3.6962E-08
2	2	-9.7975E-13	9.5991E-26	4.8815E-08	3.6962E-08
0	3	-1.3655E-10	9.3224E-21	4.8815E-08	3.6962E-08
1	3	1.8809E-10	5.8961E-21	4.8815E-08	3.6962E-08
2	3	1.0564E-11	1.1161E-23	4.8815E-08	3.6962E-08
0	4	1.0464E-11	5.4751E-23	4.8815E-08	3.6962E-08
1	4	-3.5145E-13	2.0586E-26	4.8815E-08	3.6962E-08
2	4	-9.1992E-13	8.4625E-26	4.8815E-08	3.6962E-08
0	5	1.4092E-11	9.9299E-23	4.8815E-08	3.6962E-08
1	5	-7.8389E-13	1.0241E-25	4.8815E-08	3.6962E-08
2	5	2.7719E-13	7.6837E-27	4.8815E-08	3.6962E-08
0	6	-2.6485E-04	3.5072E-08	8.3887E-08	1.8560E-09
1	6	9.3212E-07	1.4481E-13	8.3887E-08	1.8559E-09
2	6	-2.5202E-06	6.3512E-13	8.3888E-08	1.8551E-09
0	7	2.0140E-11	2.0282E-22	8.3888E-08	1.8551E-09
1	7	1.4266E-12	3.3919E-25	8.3888E-08	1.8551E-09
2	7	-6.3197E-14	3.9939E-28	8.3888E-08	1.8551E-09
0	8	3.3000E-12	5.4450E-24	8.3888E-08	1.8551E-09
1	8	3.7180E-13	2.3040E-26	8.3888E-08	1.8551E-09
2	8	-4.7771E-13	2.2821E-26	8.3888E-08	1.8551E-09
0	9	2.3473E-10	2.7550E-20	8.3888E-08	1.8551E-09
1	9	2.4344E-11	9.8770E-23	8.3888E-08	1.8551E-09
2	9	-3.8934E-10	1.5159E-20	8.3888E-08	1.8551E-09
0	10	1.8511E-11	1.7133E-22	8.3888E-08	1.8551E-09
1	10	5.7895E-14	5.5864E-28	8.3888E-08	1.8551E-09
2	10	-1.0806E-12	1.1678E-25	8.3888E-08	1.8551E-09
0	11	4.1246E-12	8.5061E-24	8.3888E-08	1.8551E-09
1	11	4.5082E-13	3.3874E-26	8.3888E-08	1.8551E-09
2	11	-5.0601E-14	2.5605E-28	8.3888E-08	1.8551E-09
0	12	-5.6761E-05	1.6109E-09	8.5499E-08	2.4009E-10
1	12	2.2400E-07	8.3627E-15	8.5499E-08	2.4008E-10
2	12	-1.4395E-06	2.0721E-13	8.5499E-08	2.3983E-10
0	1	9.2681E-13	4.2949E-25	8.5499E-08	2.3983E-10
1	1	-9.7645E-14	1.5891E-27	8.5499E-08	2.3983E-10
2	1	-3.2077E-13	1.0289E-26	8.5499E-08	2.3983E-10

0	2	-1.7843E-12	1.5919E-24	8.5499E-08	2.3983E-10
1	2	-5.0394E-13	4.2326E-26	8.5499E-08	2.3983E-10
2	2	-8.0107E-13	6.4172E-26	8.5499E-08	2.3983E-10
0	3	-6.1827E-12	1.9113E-23	8.5499E-08	2.3983E-10
1	3	5.8920E-13	5.7859E-26	8.5499E-08	2.3983E-10
2	3	-7.3863E-13	5.4558E-26	8.5499E-08	2.3983E-10
0	4	-2.9605E-12	4.3822E-24	8.5499E-08	2.3983E-10
1	4	-3.5473E-13	2.0972E-26	8.5499E-08	2.3983E-10
2	4	2.7791E-13	7.7234E-27	8.5499E-08	2.3983E-10
0	5	-3.9319E-12	7.7297E-24	8.5499E-08	2.3983E-10
1	5	-8.7941E-13	1.2889E-25	8.5499E-08	2.3983E-10
2	5	6.5685E-13	4.3145E-26	8.5499E-08	2.3983E-10
0	6	1.2409E-11	7.6988E-23	8.5499E-08	2.3983E-10
1	6	3.5834E-13	2.1401E-26	8.5499E-08	2.3983E-10
2	6	3.2676E-13	1.0677E-26	8.5499E-08	2.3983E-10
0	7	-1.0359E-11	5.3653E-23	8.5499E-08	2.3983E-10
1	7	-4.6184E-13	3.5549E-26	8.5499E-08	2.3983E-10
2	7	9.5191E-13	9.0613E-26	8.5499E-08	2.3983E-10
0	8	1.9678E-12	1.9362E-24	8.5499E-08	2.3983E-10
1	8	-5.7029E-13	5.4205E-26	8.5499E-08	2.3983E-10
2	8	-3.8622E-13	1.4917E-26	8.5499E-08	2.3983E-10
0	9	-5.9050E-12	1.7435E-23	8.5499E-08	2.3983E-10
1	9	3.5388E-13	2.0872E-26	8.5499E-08	2.3983E-10
2	9	-4.3834E-13	1.9214E-26	8.5499E-08	2.3983E-10
0	10	-1.1127E-11	6.1906E-23	8.5499E-08	2.3983E-10
1	10	-1.7901E-13	5.3405E-27	8.5499E-08	2.3983E-10
2	10	-1.3664E-12	1.8669E-25	8.5499E-08	2.3983E-10
0	11	1.2138E-11	7.3670E-23	8.5499E-08	2.3983E-10
1	11	-1.7454E-13	5.0774E-27	8.5499E-08	2.3983E-10
2	11	-5.1284E-13	2.6301E-26	8.5499E-08	2.3983E-10
0	12	2.9526E-11	4.3590E-22	8.5499E-08	2.3983E-10
1	12	6.4938E-13	7.0283E-26	8.5499E-08	2.3983E-10
2	12	2.3701E-13	5.6175E-27	8.5499E-08	2.3983E-10

EP301

POLYNOMIAL COEFFICIENT SUMMARY

TYPE OF POLYNOMIALS: LEG/FOUR
OF POLY'S (LEG, FOUR, TOT): 3 12 75
OF GOOD DATA POINTS: 7560
SIGMA**2 OF ACTUAL DATA: 2.0658E-05

L	INDECES MCOS MSIN	COEFFICIENT VALUE	SIGMA**2 OF POLY #I	SIGMA**2 OF POLY'S 1 TO I	SIGMA**2 OF DATA - POLY'S
0		-3.4226E-03	1.1714E-05	1.1714E-05	6.6205E-06
1		1.2720E-05	5.3931E-11	1.1714E-05	8.9296E-06
2		-4.1795E-05	3.4936E-10	1.1714E-05	8.9292E-06
0 1		3.9033E-10	7.6180E-20	1.1714E-05	8.9292E-06
1 1		-9.7180E-12	1.5740E-23	1.1714E-05	8.9292E-06
2 1		-1.8044E-11	3.2559E-23	1.1714E-05	8.9292E-06
0 2		3.4995E-11	6.1232E-22	1.1714E-05	8.9292E-06
1 2		-1.2549E-12	2.6246E-25	1.1714E-05	8.9292E-06
2 2		-7.6945E-12	5.9205E-24	1.1714E-05	8.9292E-06
0 3		-8.1158E-10	3.2933E-19	1.1714E-05	8.9292E-06
1 3		5.0882E-10	4.3149E-20	1.1714E-05	8.9292E-06
2 3		3.1040E-10	9.6347E-21	1.1714E-05	8.9292E-06
0 4		1.6638E-10	1.3841E-20	1.1714E-05	8.9292E-06
1 4		2.6258E-12	1.1491E-24	1.1714E-05	8.9292E-06
2 4		-1.6674E-11	2.7801E-23	1.1714E-05	8.9292E-06
0 5		2.3105E-10	2.6691E-20	1.1714E-05	8.9292E-06
1 5		-1.4625E-12	3.5648E-25	1.1714E-05	8.9292E-06
2 5		-2.2718E-11	5.1611E-23	1.1714E-05	8.9292E-06
0 6		-4.1154E-03	8.4681E-06	2.0183E-05	4.4893E-07
1 6		1.5639E-05	4.0765E-11	2.0183E-05	4.4889E-07
2 6		-5.9103E-05	3.4932E-10	2.0183E-05	4.4846E-07
0 7		3.1270E-10	4.8891E-20	2.0183E-05	4.4846E-07
1 7		-2.9197E-12	1.4208E-24	2.0183E-05	4.4846E-07
2 7		-4.5713E-12	2.0897E-24	2.0183E-05	4.4846E-07
0 8		5.4335E-11	1.4761E-21	2.0183E-05	4.4846E-07
1 8		-9.0758E-12	1.3728E-23	2.0183E-05	4.4846E-07
2 8		-7.2630E-12	5.2752E-24	2.0183E-05	4.4846E-07
0 9		3.2390E-09	5.2455E-18	2.0183E-05	4.4846E-07
1 9		-1.2991E-09	2.8129E-19	2.0183E-05	4.4846E-07
2 9		-8.2043E-10	6.7311E-20	2.0183E-05	4.4846E-07
0 10		2.9133E-10	4.2437E-20	2.0183E-05	4.4846E-07
1 10		-4.8490E-12	3.9187E-24	2.0183E-05	4.4846E-07
2 10		-1.1942E-11	1.4260E-23	2.0183E-05	4.4846E-07
0 11		5.3352E-11	1.4232E-21	2.0183E-05	4.4846E-07
1 11		-5.3339E-12	4.7418E-24	2.0183E-05	4.4846E-07
2 11		-1.6621E-11	2.7627E-23	2.0183E-05	4.4846E-07
0 12		-8.8192E-04	3.8889E-07	2.0572E-05	5.8090E-08
1 12		3.7921E-06	2.3967E-12	2.0572E-05	5.8088E-08
2 12		-3.3578E-05	1.1275E-10	2.0572E-05	5.7951E-08
0 1		1.9583E-12	1.9174E-24	2.0572E-05	5.7951E-08
1 1		-7.0247E-12	8.2245E-24	2.0572E-05	5.7951E-08
2 1		7.6689E-13	5.8812E-26	2.0572E-05	5.7951E-08

0	2	-2.3102E-11	2.6684E-22	2.0572E-05	5.7951E-08
1	2	3.1013E-12	1.6030E-24	2.0572E-05	5.7951E-08
2	2	9.1490E-12	8.3705E-24	2.0572E-05	5.7951E-08
0	3	-1.0183E-10	5.1851E-21	2.0572E-05	5.7951E-08
1	3	3.6191E-13	2.1830E-26	2.0572E-05	5.7951E-08
2	3	-1.1379E-12	1.2949E-25	2.0572E-05	5.7951E-08
0	4	-4.6533E-11	1.0827E-21	2.0572E-05	5.7951E-08
1	4	-9.8977E-12	1.6327E-23	2.0572E-05	5.7951E-08
2	4	-4.0246E-12	1.6197E-24	2.0572E-05	5.7951E-08
0	5	-6.1722E-11	1.9048E-21	2.0572E-05	5.7951E-08
1	5	-6.9008E-13	7.9368E-26	2.0572E-05	5.7951E-08
2	5	-3.2509E-12	1.0569E-24	2.0572E-05	5.7951E-08
0	6	1.8948E-10	1.7951E-20	2.0572E-05	5.7951E-08
1	6	9.2870E-12	1.4375E-23	2.0572E-05	5.7951E-08
2	6	-4.7971E-12	2.3012E-24	2.0572E-05	5.7951E-08
0	7	-1.7552E-10	1.5404E-20	2.0572E-05	5.7951E-08
1	7	-1.9787E-12	6.5257E-25	2.0572E-05	5.7951E-08
2	7	-1.9985E-12	3.9941E-25	2.0572E-05	5.7951E-08
0	8	2.9935E-11	4.4805E-22	2.0572E-05	5.7951E-08
1	8	-4.8217E-12	3.8748E-24	2.0572E-05	5.7951E-08
2	8	-5.4270E-14	2.9453E-28	2.0572E-05	5.7951E-08
0	9	-1.0109E-10	5.1092E-21	2.0572E-05	5.7951E-08
1	9	5.1847E-12	4.4801E-24	2.0572E-05	5.7951E-08
2	9	3.1072E-12	9.6547E-25	2.0572E-05	5.7951E-08
0	10	-1.7260E-10	1.4896E-20	2.0572E-05	5.7951E-08
1	10	-1.2851E-12	2.7525E-25	2.0572E-05	5.7951E-08
2	10	-8.6703E-12	7.5174E-24	2.0572E-05	5.7951E-08
0	11	1.7874E-10	1.5974E-20	2.0572E-05	5.7951E-08
1	11	-3.3887E-12	1.9139E-24	2.0572E-05	5.7951E-08
2	11	3.6722E-12	1.3485E-24	2.0572E-05	5.7951E-08
0	12	4.5769E-10	1.0474E-19	2.0572E-05	5.7951E-08
1	12	9.1936E-12	1.4087E-23	2.0572E-05	5.7951E-08
2	12	-1.1375E-12	1.2939E-25	2.0572E-05	5.7951E-08

The tolerances listed above were provided to GSFC and have been used in the EU design process. Achievement of these tolerances has proven difficult, so I thought that it would be valuable to present in more detail how they were arrived at.